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THEORY AND DESIGN OF ELECTRICAL ROTATING MACHINERY.(U)
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THEORY AND DESIGN OF ELECTRICAL
ROTATING MACHINERY

Annual Report for Period
Ending October 31, 1978

LEVEL III

A047177

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Submitted to
Office of Naval Research
in December 1978

Principal Investigator:
W. J. Carr, Jr.

Sponsored by:
Power Program ONR Contract No. N00014-72-C-0432

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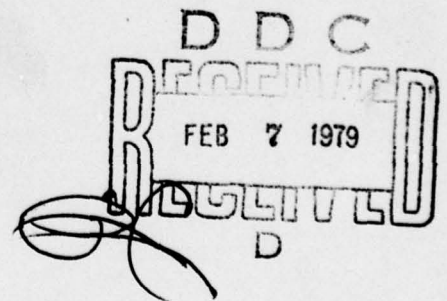
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objective of this program is to contribute toward new and improved rotating machines for Naval applications, with emphasis on superconducting machinery. Work has been performed on the theory of ac losses in multifilament superconductors and experiments were made to check the theory. A list of publications and abstracts of scientific papers published under the contract is given.		

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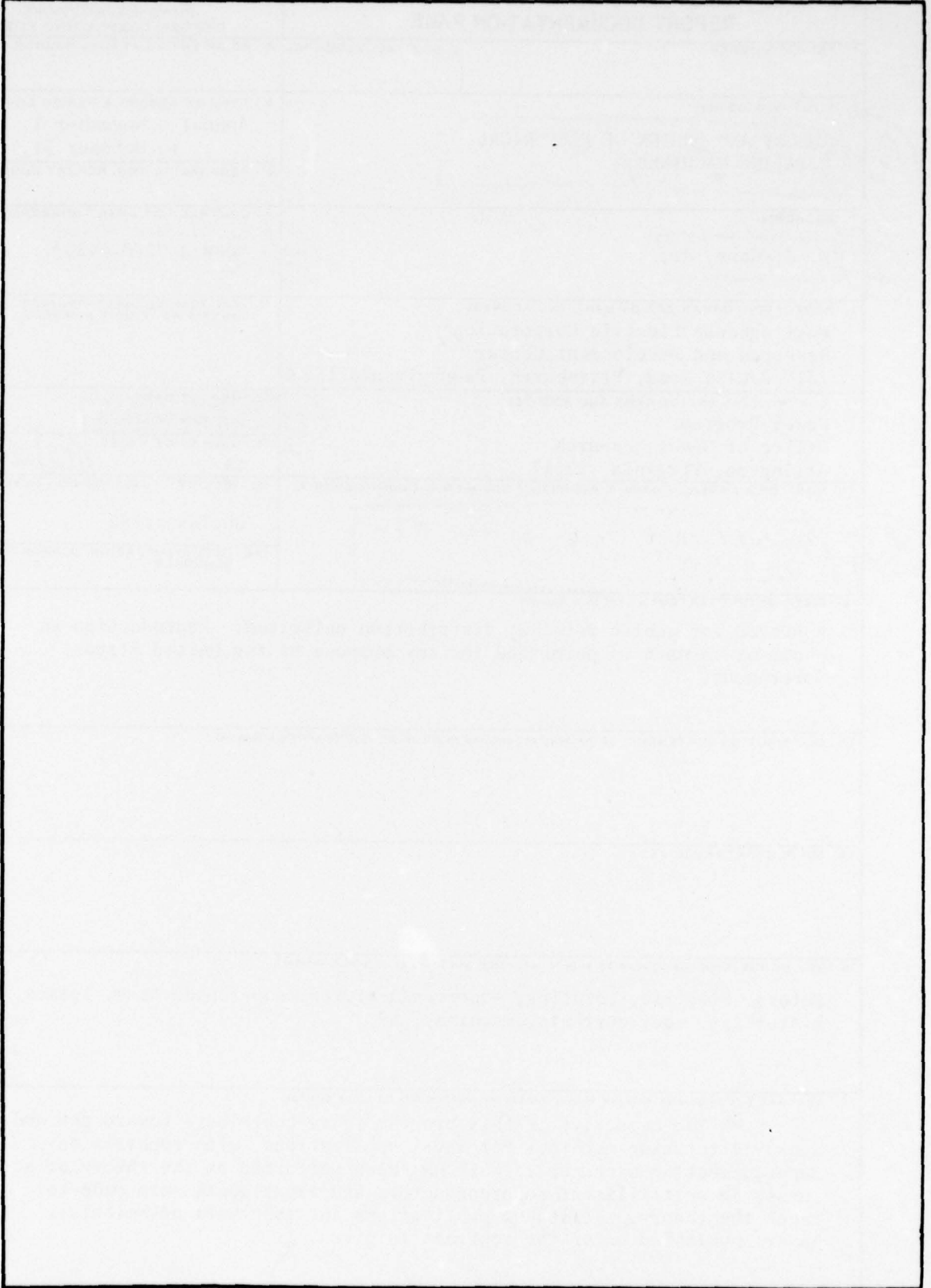
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1.0 REPORTING PERIOD

This is the sixth annual technical report and covers the work from November 1, 1977 to October 31, 1978.

2.0 OBJECTIVES

2.1 General

The objectives of the program are to contribute toward new and improved rotating machines for Naval applications, particularly in the area of superconducting machinery.

2.2 Specific

A specific objective was to study the ac loss which occurs in multifilament superconductors, with the object of providing the information needed for the design of stable low-loss conductors for use in rotating machines.

3.0 SUMMARY

Since nearly all of the work done under this contract has been published or is scheduled for publication in the scientific literature, this annual report is mainly a brief status report, along with a list of publications and references. Abstracts of all papers are listed at the end.

Approximately all of the work performed during the past year was in the study of ac losses in superconductors. This is a basic research program to study losses, with the primary objective of the program being an understanding of the various loss mechanisms, and the development of methods for accurately calculating losses under various conditions of possible interest in regard to superconducting rotating machines.

During the past year efforts were concentrated in developing methods for estimating losses in a superconductor which is acted upon by an alternating external transverse magnetic field, while carrying an arbitrary amount of in-phase transport current. The problem is extremely difficult to calculate but some curves were developed so that a reasonable estimate of the losses can be made. The results were reported at the 1978 Applied Superconductivity Conference in Pittsburgh, PA.

The main structure of the theory of ac losses in superconductors is now in place, even though there are many important details which remain to be answered. For isolated conductors in strong magnetic fields which fully penetrate the conductor, the loss formulas are sufficiently simple that they may be routinely used, and require little knowledge of superconductivity. Unfortunately this is not true of the weak field case where the conductor is partially penetrated. Much of the work under this contract has gone into a study of partial penetration. An opportunity to study this case in detail was provided by measurements made at the

University of California at Berkeley, on a number of superconducting solenoids which were built for airborne prospecting. In close collaboration with the workers at Berkeley, calculations were made for these coils and reported on at the 1978 Intermag Conference in Florence, Italy.

4.0 STUDIES OF AC LOSSES

Interest in ac loss theory and the need for more accurate calculations from the standpoint of superconducting machinery design arises in two ways: (1) where the ac loss is small and the interest is in the proper amount of cooling needed to remove the heat and (2) where the ac losses are large and form the primary design limitation. AC loss due to ripples in a dc magnetic field and loss due to slow switching of the field usually produce no problem if they are well understood and predictable, so that adequate cooling can be provided for, and a proper conductor design can be selected. The question here is reliability at minimum cost. To obtain this information entirely from the construction and testing of experimental machines would require too long a time period and would be very expensive.

The second category is connected with the possibility of using superconductors in a primarily ac field, and future hopes for revolutionary machine design. The rate of recent progress in conductor design, and in the understanding of the various loss mechanisms which dictate a given design, indicate the likelihood that superconductors can be developed for fully ac applications. The attainment of this goal would open the possibility of new designs and new types of superconducting machinery.

AC losses in multifilament superconductors are well-known to be of two types: an eddy current loss in the matrix and hysteresis loss in the filament. To obtain the former, the electric field must be known at each point in the conductor. To obtain the hysteresis loss, the magnetic field acting on each filament must be known. A large part of the problem of calculating losses in superconductors is involved in computing these fields.

5.0 PUBLICATIONS DURING THE PAST YEAR

1. W. J. Carr, Jr., Ben Clawson, and Wayne Vogen, "AC Losses in Superconducting Solenoids," IEEE Transactions on Magnetism, Vol. MAG-14, 617 (1978).

Abstract: Losses were measured in a variety of different solenoids made from various types of superconductors. Both single filament and multifilament, twisted and untwisted, conductors were used. The results were compared with calculated losses for these cases.

2. W. J. Carr, Jr., "AC Loss from the Combined Action of Transport Current and Applied Field," To appear in the Proceedings of the 1978 Applied Superconductivity Conference, 1978.

Abstract: The ac loss in a superconductor resulting from the combined action of an alternating transport current and in-phase ac transverse field is calculated for a slab, and normalized in a form which can be applied approximately to a circular wire. Some results for limiting cases are also directly calculated for a wire.

6.0 COMPLETE LIST OF PUBLICATIONS UNDER THE CONTRACT

1. W. J. Carr, Jr., "AC Loss in a Twisted Filamentary Superconducting Wire," Journal of Applied Physics, 45:929 (1974).

Abstract: Calculations are made for the ac losses in a twisted filamentary superconductor by assuming a continuum model with anisotropic conductivity. The Maxwell equations are solved for a long wire of radius R_0 and twist length L . In terms of the classical skin depth δ , appropriate for the conductivity perpendicular to the filaments, the losses are calculated for an applied magnetic field transverse to the wire axis in the case of (1) a uniform field ($\sqrt{2} R_0/\delta < 1$, $L/2\pi\delta < 1$), (2) shielding from surface currents ($\sqrt{2} R_0/\delta < 1$, $L/2\pi\delta > 1$), and (3) skin effect ($\sqrt{2} R_0/\delta > 1$). Losses are also calculated for the case of a transport current in no applied field. The model can be used in more general cases and has the virtue of giving precise results with a minimum of auxiliary postulates.

2. W. J. Carr, Jr., "AC Loss in a Twisted Filamentary Superconducting Wire II," Journal of Applied Physics, 45:935 (1974).

Abstract: Hysteresis losses in a twisted filamentary superconducting wire are calculated for various cases corresponding to complete penetration of the magnetic field into the wire, shielding of the field by the supercurrents, and shielding due to eddy currents. In general, the wire may be divided into two regions: an outer saturated layer which tends to behave at the higher frequencies like a solid superconductor, and the interior where the average parallel electric field vanishes and the wire behaves like a collection of individual filaments.

3. J. H. Murphy, M. S. Walker, and W. J. Carr, Jr., "Theory of Alternating Field Losses in Cylindrical Twisted Multifilamentary Superconductors," Intermag Conf. Proc., IEEE Trans. Mag., 10:868 (1974).

Abstract: The theory of sinusoidal alternating field losses in a cylindrical multifilamentary superconducting wire is discussed. Hysteresis loss expressions are presented for the individual filament losses in the interior of the wire when these filaments are completely penetrated, and for the loss occurring in an outer current-saturated layer of the wire. The loss expressions presented were determined assuming a continuum model with anisotropic conductivity for the superconductor. The case of a permeability different from unity, applicable for weak fields, is discussed.

4. W. J. Carr, Jr., "Electromagnetic Theory for Filamentary Superconductors," Physical Review B, 11:1547 (1975).

Abstract: It is shown that a multifilament superconductor, made up of a bundle of twisted filaments embedded in a normal matrix, can be treated as a new state of matter with anisotropic electrical and magnetic properties. Macroscopic electromagnetic field vectors, which satisfy Maxwell's equations, are defined in terms of averages over the "microscopic" fields. However, the sources for the field, i.e., the current and charge densities and the magnetization and polarization, differ in some respects from those for ordinary matter. In particular, since the elementary magnetic dipole moments are distributed along lines rather than located at fixed points, the definition of the magnetization transverse to the filaments differs by a factor of 2 from that for ordinary matter, and the definition of the macroscopic current density is also slightly modified. Constitutive relationships among the field vectors in terms of permeabilities, dielectric constants, and conductivities are examined in the limits of strong and weak fields.

5. W. J. Carr, Jr., "Conductivity, Permeability and Dielectric Constant in a Multifilament Superconductor," Journal of Applied Physics, 46:4043 (1975).

Abstract: Results are given for the permeability, conductivity, and dielectric constant of a multifilament superconductor, treated as an anisotropic state of matter. The calculations are made for the limiting cases of strong and weak ac magnetic fields compared with the field required for complete penetration of the filaments. General expressions are given for the ac power loss.

6. W. J. Carr, Jr., M. S. Walker, and J. H. Murphy, "Alternating Field Loss in a Multifilament Superconducting Wire for Weak AC Fields Superposed on a Constant Bias," Journal of Applied Physics, 46:4048 (1975).

Abstract: Expressions are given for the alternating field loss in a twisted filamentary superconductor as a function of frequency and magnetic field, for the case of small ac applied fields which do not completely penetrate the filaments. The ac field is superimposed on a fixed bias field. In this limit the effective diamagnetism of the filament leads to a permeability less than unity for the composite. Expressions are presented for both the hysteresis and the eddy current loss.

7. M. S. Walker, W. J. Carr, Jr., and J. H. Murphy, "Loss Behavior in Twisted Filamentary Superconductors," IEEE Trans. on Magnetics, MAG-11, 1475 (1975).

Abstract: A careful comparison between theory and experiment is made for the transverse alternating field eddy current losses in three twisted mixed-matrix filamentary superconductors of the composition $3\text{CuNi}:3\text{Cu}:1\text{NbTi}$. The measurements were made over a wide frequency range, up to 10^6 Hz. Good agreement is obtained.

8. W. J. Carr, Jr., "Possibility for an All-Superconducting Synchronous Motor or Generator," Westinghouse Research Report 73-9J2-MACON-R1.

Abstract: Possibilities for a motor or generator with superconducting armature and field winding are discussed, and the ac losses that would be expected in the armature winding are calculated.

9. W. J. Carr, Jr., "Design Theory for a Fully Superconducting Synchronous Motor or Generator," Westinghouse Research Report 73-9J2-MACON-R2.

Abstract: Theory is developed for a superconducting synchronous motor or generator having both the field and the armature windings superconducting. An approximate design is given for a four-pole 30 MW operating at 180 rpm.

10. J. H. Murphy and W. J. Carr, Jr., "Eddy Current Losses in Twisted Multifilamentary Superconductors," Westinghouse Research Report 73-9J2-MACON-R3.

Abstract: Calculations are made for the eddy current losses in a multifilament superconductor having a copper sheath.

11. L. N. Wedman, "A Low Speed Direct Current Superconducting Heteropolar Motor," Report EM4562.

Abstract: Important progress in assessing the limits of ratings for new concept electrical machines for ship propulsion applications has been achieved. The superconducting heteropolar motor has been identified as the most promising machine concept for slow-speed, high-power use. Maximum utilization of the drum homopolar machine is limited by transmission line current ratings, and may be greatly improved if an in-line drive is required, thus allowing the use of the homopolar torque converter. The magnetic disc homopolar motor with water cooling appears to be the preferred concept for low-speed homopolar motor applications. Technical progress in the conceptual configuration of the superconducting

heteropolar machine is presented, together with a report on progress on the solution of commutation problems in such machines.

12. W. J. Carr, Jr., M. S. Walker, D. W. Deis, and J. H. Murphy, "Hysteresis Loss in a Multifilament Superconductor," *Advances in Cryogenic Engineering*, 22, 428 (1977).

Abstract: Theory of hysteresis loss in a multifilament superconductor is reviewed and measurements are presented for a mixed-matrix NbTi conductor. The measurements were made calorimetrically as a function of frequency and transverse ac magnetic field, for a 50 kOe dc bias field, and also with no bias. Both a linear ac field dependence and a cubic field dependence were observed, corresponding to the case of complete penetration of the filaments, and partial penetration. Comparison of experiment with calculation was made by evaluating the critical current density from the measurements and the loss expression, and comparing this value with a direct measurement of j_c from transport current. Good agreement was obtained.

13. W. J. Carr, Jr., "Parallel Field Losses in Twisted Multifilament Superconductors," *Sixth Symposium on Engineering Problems of Fusion Research*, IEEE Pub. No. 75CH1097-5-NPS (1975), p. 152.

Abstract: In some applications of multifilament superconducting wire an appreciable component of a time dependent magnetic field exists along the twisted filaments, and across the matrix, and loss and stability problems are introduced. It has been suggested by various authors that these effects can be minimized by periodically introducing reverse twist in the wire. A calculation is given for the eddy current loss that can be expected for such a conductor. The calculation also applies for the case where the twist is uniform but the direction of the magnetic field reverses along the length of the conductor.

14. W. J. Carr, Jr., "Longitudinal and Transverse Field Losses in Multifilament Superconductors," IEEE Transactions on Magnetics, Vol. MAG-13, 192 (1977).

Abstract: A review is given of the method of calculating losses in a composite twisted multifilament superconductor based on the anisotropic continuum model, and a summary of results are shown for the loss as a function of frequency due to longitudinal and transverse applied fields. In both cases three frequency ranges may be distinguished in which (1) the magnetic field in the superconductor is just the applied field, (2) the field produced by internal currents becomes important, and (3) skin effect develops in the eddy currents, which flow transverse to the filaments. In addition to these losses in the body of the superconductor (characterized by a vanishing component of electric field parallel to the filament axes), the losses in the current saturated boundary layer is described. Some discussion is also given on the use of ac field losses in calculating the "ramped" field case.

15. W. J. Carr, Jr., "Longitudinal Field Losses in Multifilament Superconductors over a Range of Frequencies," J. Appl. Phys., 2022 (1977).

Abstract: The power loss in a twisted multifilament superconductor due to a time-dependent longitudinal magnetic field is calculated as a function of frequency. The longitudinal field is assumed to have a sinusoidal dependence on both space and time, alternating changing direction along the conductor over a length ℓ . The eddy current loss, as a function of frequency, initially is approximately proportional to ℓ^2 and rises as the square of the frequency, until it reaches a plateau which tends to be frequency independent and inversely proportional to ℓ^2 . After a further increase with frequency, the skin effect region is reached with frequency to the one-half power dependence. The current-density distribution in the conductor is calculated, and it is shown that for large ℓ the entire cross section of the conductor can become current saturated if the amplitude of the ac field is greater than $L\lambda j_c$ where L is the twist length, j_c is the critical current density, and λ is the fraction of superconductor.

16. W. J. Carr, Jr., J. H. Murphy, and G. R. Wagner, "Alternating Field Losses in Filamentary Superconductor Carrying DC Transport Current," Advances in Cryogenic Engineering, Volume 24, 415 (1978).

Abstract: Alternating field losses in multifilament superconductors have been calculated previously only for special limiting cases, i.e., for the case of full field penetration of the filaments, or for the case of no transport current. From these limiting values interpolation formulas are given here for the full range of alternating field and dc transport current, assuming only that the frequency is below the critical frequencies for internal field effects, and that saturation effects in the outer filaments may be neglected. The results are compared with some measurements.

17. W. J. Carr, Jr., "Magnetic Circuit Design for a Homopolar Motor," Westinghouse Research Report 76-9C30-MACON-P2. Presented to the Winter Meeting IEEE Power Engineering Society in New York, January 1978.

Abstract: The use of iron to enhance the flux density in a homopolar machine is limited by the presence of a large circumferential field which tends to saturate the iron in the wrong direction. It is shown that the use of an iron structure with optimized circumferential gaps can overcome this difficulty, and in many cases eliminate the necessity of a compensating current.

18. W. J. Carr, Jr., Ben Clawson, and Wayne Vogen, "AC Losses in Superconducting Solenoids," IEEE Transactions on Magnetics, Vol. MAG-14, 617 (1978).

Abstract: Losses were measured in a variety of different solenoids made from various types of superconductors. Both single filament and multifilament, twisted and untwisted, conductors were used. The results were compared with calculated losses for these cases.

19. W. J. Carr, Jr., "AC Loss from the Combined Action of Transport Current and Applied Field," To appear in the Proceedings of the 1978 Applied Superconductivity Conference, 1978.

Abstract: The ac loss in a superconductor resulting from the combined action of an alternating transport current and in-phase ac transverse field is calculated for a slab, and normalized in a form which can be applied approximately to a circular wire. Some results for limiting cases are also directly calculated for a wire.

7.0 PROGRAM PERSONNEL

The personnel who have contributed to this program are as follows:

W. J. Carr, Jr. - Consultant in Magnetism and Superconductivity

J. H. Murphy - Engineer, Cryogenics

G. R. Wagner - Physicist, Cryogenics.

Consultation has been provided by other members of the Machinery and Cryogenics Groups.

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